A High Efficiency Electron Cyclotron Resonance Ion Source System For The Production Of Radioactive Ion Beams

Final Report
of
A DOE99 SBIR Phase I Project
(Grant No: DE-FG-99ER82750)

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PROJECT SUMMARY
Phase I

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Topic No. (1-40)   Subtopic (a-d)

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PROJECT TITLE: **A High Efficiency Electron Cyclotron Resonance Ion Source System for the Production of Radioactive Ion Beams**

DOE99SBIR Grant No: **DE-FG-99ER82750**

TECHNICAL ABSTRACT (Limit to space provided)

Statement of the problem or situation that is being addressed - typically, one to three sentences.

This Project results in the development of a high efficiency, high charge state electron cyclotron resonance ion source system for the production of rare ion beams supported by the Department of Energy.

General statement of how this problem is being addressed. This is the overall objective of the combined Phase I and Phase II projects - typically, one to two sentences.

Develop a high performance electron cyclotron resonance ion source with a hot plasma chamber liner to increase the ionization efficiency. Use a thermal transfer line between the production target and the ion source to reduce the radiation damage to the ion source.

What was done in the Phase I project (typically, two to three sentences)?

Determined a set of optimum parameters for a high efficiency, high charge state, permanent magnet electron cyclotron resonance ion source, a hot liner and a medium temperature oven for the production of solid isotopes. Reviewed the radiation levels and damage to the permanent magnet materials. Completed the engineering design and the cost estimates for the ion source system, including the conceptual layout of a test bench for characterizing the source system at Berkeley Ion Equipment, Inc. and at a national facility operated by the Department of Energy.

COMMERCIAL APPLICATIONS AND OTHER BENEFITS as described by the applicant. (Limit to space provided)

In addition to the applications in the production of rare isotope beams in nuclear science research, the developed permanent magnet electron cyclotron resonance ion source can be used in other areas: such as an ion injector for heavy ion accelerators, atomic physics and applied science. Applications of this ion system can be found in industry for high energy ion implantation, ion milling and material surface modification.

SUMMARY FOR MEMBERS OF CONGRESS: (LAYMAN'S TERMS, TWO SENTENCES MAX.)

Improve the ionization efficiency of the high charge state rare ions for rare ion beam generation for nuclear science research. Develop a high efficiency permanent magnet electron cyclotron resonance ion source system.

1. SCIENTIFIC SIGNIFICANCE

Currently there are worldwide efforts to produce rare isotope beams (RIBs) to study the structures of nucleus far from stability and stellar evolution. Experiments with RIBs are to provide answers to many questions concerning astrophysics and nuclear physics, such as nuclear structure, element formation, the standard model, etc. It can also provide new techniques for materials and medical research in applied science.

Several US DOE national facilities are pursuing RIB capability, such as the ATLAS facility at Argonne National Laboratory, the Holifield Facility at Oak Ridge National Laboratory and the BEARS initiative (Berkeley Experiments with Accelerated Radioactive Species) at the 88-Inch Cyclotron Facility of Berkeley National Laboratory. These facilities have achieved certain progress as evidenced in providing a few RIBs for nuclear experiments. A benchmark facility (RIA) using the isotope separator on-line technique (ISOL) for the production of RIBs has been proposed and construction may begin in the near future. However, RIB production is much more complex than the production of stable ion beams. More research and development is needed to further increase the production efficiency, especially in the areas of production target and ionization.

Because of the low reaction cross-sections and practical limits on radiation levels and the production targets, the yields of the rare isotopes at the production target is expected to be in the range of a few x 10^2 to 10^{13} atoms/second depending upon species. Therefore even with 100% efficiency, the RIB intensity will often be orders of magnitude lower than most stable ion beams. In addition, there can be severe isobar contamination due to other rare species of the same mass produced at the same time. In some cases a very high resolution separator or stripping is required to purify the ion beams if the impurity is not tolerated by the experiments. Most of the rare species far from stability are short-lived in which the decay loss is inevitable given by nature, though it can be minimized by rapid transport to experiments. While many nuclear experiments require accelerated RIBs with as high intensity as possible, the low yield, decay loss and isobar contamination pose a great challenge to the RIB production. Therefore the efficiency of every part, i.e., target production, transport, ionization and acceleration, of the system is the key to the success of the RIB production.

Existing accelerator technology will be used to accelerate the rare ions to meet the nuclear experiment requirements. The total ion energy E produced by accelerators is proportional to the

ion charge state Q (linacs, tandems and RFQs) or to Q^2 (cyclotrons). This relation between the energy and the ion charge state manifests the advantage of the high charge state rare ions. So with the higher charge state ion beams, an accelerator can be built smaller with lower cost for the same ion energy achieved by accelerating the low charge state ions or an accelerator can be designed and built to produce higher energy ion beams. A simple system or device that can efficiently and reliably produce the high charge states RIBs for post-acceleration would be very preferable for the RIB production.

2. PHASE I TECHNICAL OBJECTIVES

The objectives of this SBIR99 Phase I are to evaluate the basic parameters, such as the magnetic and mechanical structure of the ion source, the hot liner and the thermal transfer line. Calculations with computer codes, such as POISSON, PANDIRA, PERMAG and thermal analysis, are performed to determine the ion source magnetic field configuration, microwave launching mechanisms, the hot plasma chamber liner and transfer line temperature control and thermal insulation. After reaching a set of optimum parameters, detailed engineering designs for each main component of the proposed system will be made with cost estimates. These results are the basis for fabrication of the proposed system for Phase II or III R&D period and collaborations with the DOE's national facilities.

3. PARAMETERS FOR A HIGH PERFORMANCE ECR ION SOURCE

3.1 The Effects of Magnetic Field Strengths on ECR Ionization Efficiency

The magnetic field strengths of an ECR ion source serve both to confine the plasma and to provide a relatively thin heating surface where the microwave power can efficiently heat the plasma electrons through electron cyclotron resonance. Both the quality of the confinement and the size and shape of the ECR zone where the electron heating takes place are important for efficient ionization. A quantitative relationship of the magnetic field strength to the ionization efficiency of specific ion species remains to be investigated.

The basic field geometry for ECR sources producing multiply charged ions is a minimum-B configuration that provides an increasing field in any direction away from the central minimum. A solenoidal field with strong mirrors reflecting the electrons at injection and extraction produces confinement in the axial direction. A multipolar field produces confinement in the

radial direction, typically a sextupole in which the field strength increases as the square of the radius. To produce hot electrons needed for ionization in the plasma, it is necessary for the electrons to pass through the ECR heating zone many times without suffering a collision with the plasma chamber walls. This means that the ECR zone must be a closed surface and these surfaces are typically egg shaped.

The basic geometry for a closed ECR zone is defined by

$$B_{ecr} = 2\pi f m_e/e$$

where B_{ecr} is the magnetic field strength at resonance, f is the operating microwave frequency, m_e is the electron mass and e is the electron charge. There are still a variety of options with respect to the magnetic field design. For example, when multiple frequencies of microwaves are launched into the ECR plasma, multiple closed ECR surfaces are produced due to the magnetic field gradients. The production of high charge state ions requires a compromise between the confinement, needed to trap the ions for sufficient time so they can be ionized to high charge states, and the extraction, needed to produce a beam. This is done by providing a magnetic field geometry where the weakest point along the plasma chamber surfaces is located at the extraction aperture. Experimental evidence shows that the ECR ion source performance improves as the ratios of the maximum fields B to B_{ecr} at injection and the chamber wall are increased from 1 to 2 but are relatively insensitive above 2.(1) The minimum axial field at the center of the ECR should be roughly 80% of B_{ecr}, lower values result in some loss in performance. The gradient of the magnetic field at the resonance zone affects the heating rate of the electrons, with low gradients give faster heating rates. Low gradients are advantageous for the production of very high charge state ions where very high electron energies are needed. However, they are less important for the production of intermediate charge state ion beams as has been demonstrated by the CAPRICE source.(2) For permanent magnet ECR sources, the field gradients are basically determined by the field strengths and spacing of the two magnetic mirrors.

The overall magnetic field design guidelines for a high performance ECR ion source are listed in Table 1. An ECR magnetic field configuration following these guidelines should provide very efficient ionization to the intermediate and high charge states that is crucial for applications with rare isotope beam production. Such a field configuration will not only support a high-density plasma that increases the probability of ionization of the neutral atoms in a single

pass through the plasma but also sufficiently confine the ions to be ionized to higher charge states. In addition the minimum B configuration with strong fields at the walls improves the confinement of the ions and reduces the loss of the ions through collisions with the plasma chamber walls.

Table 1. Design guidelines for the ECR magnetic fields

B_{wall}/B_{ecr}	~2
B_{inj}/B_{ecr}	~2
B_{ext}	$< B_{wall}$ and B_{inj}
Minimum B_{axis}	~0.8 B_{ecr}

References:

(1) S. Gammino, G. Ciavola, L Celona, M. Castro, F. Chines, and S Marletta, Review of Scientific Instruments, Vol 70, No 9, p 3577 (Sept. 1999)

(2) B. Jacquot and M. Pontonnier, Proceedings of the 10th International Workshop on ECR Ion Sources, Oak Ridge, Tenn., Nov 1990, p. 133.

3.2 Production Target Radiation Level and Damage in Permanent Magnetic Materials

From several studies [1,2,3] it is known that charged particles are very damaging to all permanent magnetic materials. Thus it is imperative that no charged particles reach the ECR ion source. If at all possible, no neutrons should either. So shielding must be arranged to attenuate the radiations.

Ions beams, typically at energies of hundreds of MeV per nucleon or higher, are used in the rare isotope production in which the produced particles are mainly in the forward direction. If appropriate shielding is used between the production target and the ion source so that essentially no charged particles reaching the ion source, the main threat to the permanent magnets is the neutrons since the photons are less damaging. One way to mitigate this problem is to place the source at a backward position in addition to providing the shielding as illustrated in Figure 1. At an angle of 135 degrees the high energy neutron flux will be reduced to about 0.25% of what it would be at a comparable distance at zero degrees.[4]

As an upper limit in the rare isotope production, at 100 kW beam power the light ion beams (in the 1 GeV energy range) will have ~100 particle microamps on the production target. This

scheme produces $\sim 10^{16}$ n/s in a 4π solid angle from the target.[5] Most of the high energy neutrons are in the forward direction, while lower energy neutrons are approximately emitted isotropically. Sine low energy neutrons are easier to shield, the ion source should be at a backward angle to reduce the high energy neutrons hitting the source magnets. Under this scenario, placing the high efficiency ECR system at such a backward angle with a distance of 2 m would result in a neutron flux of a few $x10^{11}$ n/s cm^{-2} or lower at the ion source. With additional shielding between the source and the target, the neutron flux could be attenuated to a few $x10^{10}$ n/s cm^{-2} or even lower. This will greatly prolong the ion source lifetime. Older material at elevated temperatures and high magnetic stress configurations started showing some radiation damage at about 10^{16} n/cm^2. However, this is a very pessimistic scenario, since even some of the old material showed little effect at ten times this dose. If we use the conversion factor of 10^9 n/cm^2 = 1 Rad (for fast neutrons), then the "standard" lifetime dose of 50 Mrad gives a source life of 1 to 2 years. While with the newer materials, the permanent magnet lifetime in relation to the radiation damage should be substantially longer.

There are three permanent materials that can be considered for constructing a permanent magnet ECR ion source: two SmCo types and NdFeB. The SmCo materials have different amounts of Sm and have chemical compositions of $SmCo_5$ (known as 1-5) and Sm_2Co_{17} (known as 2-17). Cost is in the order: NdFeB $<$ Sm_2Co_{17} $<$ $SmCo_5$ for the raw materials. Machining costs are about the same for these brittle materials, although NdFeB is somewhat less brittle. A much more important factor is the relative "magnetic strengths". This means the magnitude of the remanent field, B_r, and the coercivity, H_c, can conveniently be expressed as the energy density (in MGOe). The 1-5 material is substantially weaker, $<$ 16 MGOe, while the 2-17 is a little better, $<$ 28 MGOe. NdFeB is substantially better with a present maximum energy density of about 50 MGOe that is commercially available. In passing, it should be noted that the 50 MGOe maximum doesn't represent an upper limit for NdFeB and energy products of greater than 60 MGOe should be available in the not too distant future. The higher energy product of NdFeB means that a substantially smaller amount of material is needed to produce high magnetic fields and the B_r of some grades of NdFeB at 1.4 T will be able to produce fields unachievable by either of the SmCo's.
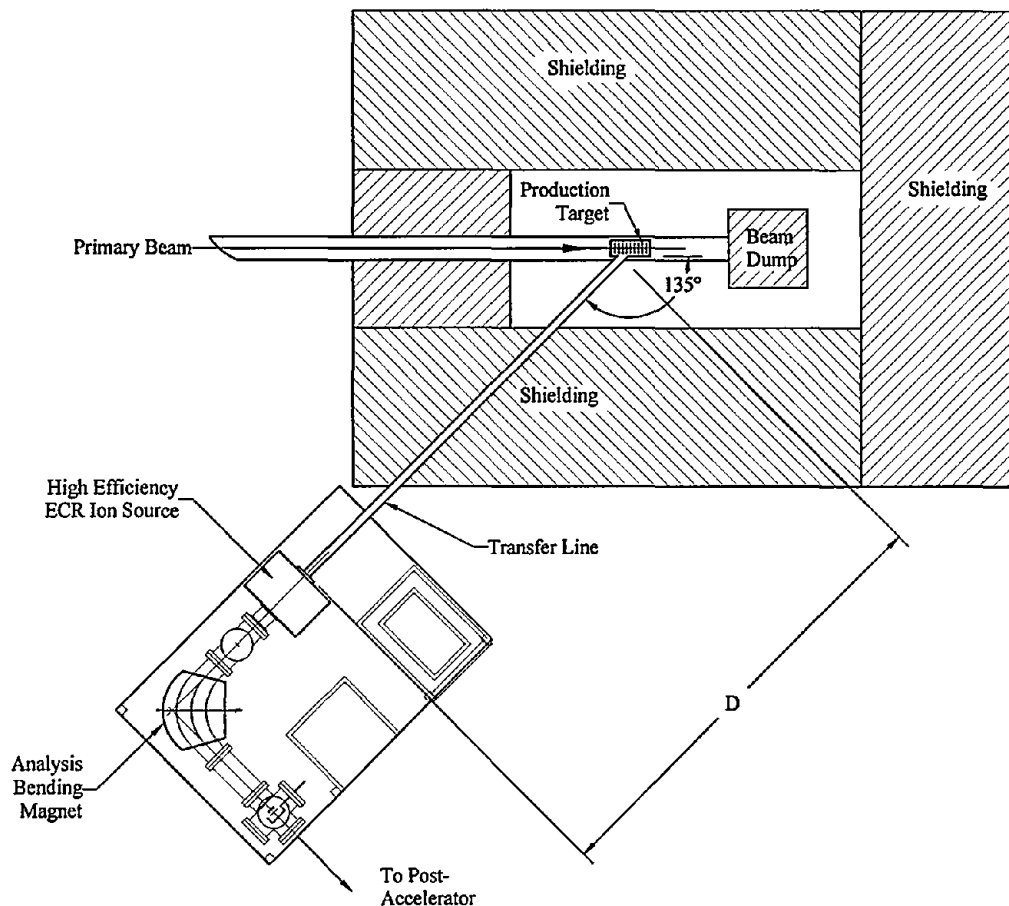
Figure 1. A schematic view of a possible set up between the high charge state ion source and the rare isotope production target. Placement of the ion source in a backward angle of 135° can substantially reduce the high energy neutron flux reaching the source magnets. The distance "D" between the production target and the ion source is to be compromised with the radiation resistance of the ion source magnets. The size and shape of the transfer line are to be determined for satisfactory isotope transport.

The problems with NdFeB are the results of its relatively low Curie temperature and its high temperature sensitivity. The Curie temperature of SmCo is about 800 °C while NdFeB is about 350 °C. Thus at relatively low temperatures which might be easily encountered in ECRs, the

NdFeB is at risk of being demagnetized at a local hot spot. In addition, the loss of B_r per $^\circ$C is 2.5 times that of SmCo (-0.04 %/$^\circ$C). Since some of this loss is irreversible a single temperature excursion can severely degrade a magnet. Although the exact mechanism for loss of permanent magnetic properties with radiation is not known, it is linked with these two properties. So a material that is resistant to thermal degradation is also resistant to radiation damage. It has been suggested that the low Curie Temperature of NdFeB is the culprit. There is some evidence for this suggestion [1] since irradiation of NdFeB at 20 $^\circ$K shows radiation resistance very much better than irradiation at room temperature or above.

There are two important ways of minimizing the damage possibilities, which apply to all of the materials under consideration. The first is material selection and the second is the magnetic circuit. The advantages of NdFeB far outweigh the advantages of SmCo, since the circuit design can overcome some of the drawbacks of the lower radiation resistance. The important parameter in choosing a particular material grade is the coercivity, H_c, the resistance to demagnetization. Every measurement of radiation damage shows the larger the coercivity, the higher the radiation damage threshold. This is more apparent in NdFeB than SmCo because of the difficulty in testing at very high doses and at room temperature all of the SmCo materials have very high coercivities. One important thing needs to be kept in mind: most of the tests on NdFeB were done ten to fifteen years ago with material energy products of 30 MGOe or less. There has been significant improvement in material properties since then. The present state of the art of NdFeB material is near 50 MGOe with very high coercivity, a commercially available material. A 1990 study [3] on NdFeB showed significant irreversible loss in NdFeB materials, in a low permeance (high demagnetization) configuration, when heated in an oven to 60 $^\circ$C. A more recent repeat of this test using newer materials, in even more magnetically stressed configurations, showed insignificant loss to 100 $^\circ$C.[6] The most recent study, done in 1995, looked for damage to magnets installed in an insertion device in a storage ring. It showed no damage at 1.2 x 10^7 Rad.[7] This is a level that would have completely destroyed magnets ten years ago. Thus there is evidence that material properties have improved to a point where NdFeB is a more viable candidate for long-term use in a radiation environment. It should be noted that materials with the highest B_rs are not the same as the ones with the highest H_cs. Generally, one has to accept a smaller energy product, and lower B_r to get a higher H_c, but these materials are readily available.

It would also be helpful, both in terms of radiation resistance and maximizing B_r, to keep the material as cool as possible. While it is not practical to operate at liquid nitrogen temperatures, 77 °K, operating at substantially under room temperature will both increase source lifetime and increase magnetic field. The complication of adding cooling, and water can not be in direct contact with the NdFeB since it readily rusts, has to be balanced with the increased source lifetime. However, unless operation at about 200 °K is practical, the gains are probably not significant enough to warrant such a cooling scheme and dealing with an organic coolant that might be radiation susceptible.

In summary, the gains from using modern NdFeB material instead of any of the SmCo materials far outweigh the potential for radiation-induced failure. The risk from using NdFeB can be alleviated by placing the ion source at a reasonable location with sufficient shielding, choosing the right material, keeping the temperature low and designing the magnetic circuit for the desired magnetic properties with minimum demagnetizing force.

References:

[1] O. –P. Kahkonen et al, *Europhysics Letters* 12, 413 (1990).

[2] E. W. Blackmore, *IEEE Trans. Nucl. Sci* 32, 3669 (1985).

[3] A. F. Zeller and J. A. Nolen, 9th Int. Workshop on Rare-Earth Magnets, 159 (1987).

[4] T. Kurosawa et al, *Nuclear Science and Technology* 36, 41 (1999).

[5] J. Nolen, private communications.

[6] A. F. Zeller, unpublished research 1995.

[7] J. Pfluger, G. Heintze and I. Vasserman, *Rev. Sci. Instrum.* 66, 1946 (1995).

3.3 A Hot Plasma Chamber Liner

One of the Phase I objectives is to evaluate a hot liner to cycle the materials deposited on the plasma chamber surfaces back into the plasma thereby to improve the ionization efficiencies, especially for the solid isotopes.

In addition to its mechanical complexity, a hot liner will reduce the ECR plasma radial confinement as both the effective radial magnetic field strength and the plasma chamber size are decreased. However, if the hot liner can improve the ionization efficiency the price will be well worth it. There are two types hot liners that can be employed in an ECR ion source; a resistively heated hot liner or an RF heated liner.

Table 2. Comparison between the RF and Resistively Heated ECR hot liners

	RF Heated Liner	*Resistively Heated Liner*
System	Simple	Complex and bulky
Operation	Easy	Not so easy
Maximum Temperature	600 °C (~Pμ of 2 kW)	1300 °C (addit'l 2 kW Pac)
Temperature Control	Passive	Active above T_{rf}*
Ac power	None	> 2 kW
Cost	~$1 k	~$8 to 10 k

T_{rf}: The maximum temperature due to the microwave heating.

Listed in Table 2 are the pros and cons of these two liners. A resistively heated liner can independently vary its temperature above the threshold heated by the microwave power but it is much more complex. It requires more space to accommodate its mechanical structure for the electrical insulation of the heating wires that will further reduce the radial plasma confinement as compared to an RF heated liner. The power needed to produce a temperature of 1300 °C will be in the order of 2 kW or higher even for a well-designed liner.(1) Additional thermal cooling is also required to avoid heating up the source permanent magnets. The ac power to the heating power supply floating at the source high potential has to be provided through an isolated transformer.

An RF heated hot liner is much more simpler in terms of the mechanical structure, cost and control, as compared to the resistively heated hot liner. It is simply a thin liner with a thickness of about 1 mm sitting inside the plasma chamber. The drawback of such an RF heated liner is that it cannot independently vary its temperature since it depends upon the input microwave

power. However it would warrant evaluation if an RF heated hot liner can provide a maximum temperature of 500 to 600 °C at the operating microwave power. A maximum temperature of 600 °C is sufficient to cover the operations for a great variety of solid isotopes for a vapor pressure of the order of 1 mTorr for ECR plasma. Therefore an RF heated liner would be a good choice for an ECR ion source.

References:

(1) R. Harkewicz, private communications.

4. DESIGN OF THE ECR ION SOURCE SYSTEM

A permanent magnet ECR source system has many advantages over a conventional ECR source built with either resistive or superconducting coils; much lower cost, easier operation and compact size for easy maintenance. It eliminates the source magnet DC power supplies, typically with power more than one hundred kW and a cost of ~$80k, in addition to the electricity and cooling cost. The elimination of the electromagnets substantially reduces the total cost, footprint and tuning parameters. In the period of this SBIR Phase I project, a high efficiency permanent magnet ECR ion source system has been designed, based on the determined parameters stated above, for the applications in rare isotope beam production.

4.1 Selection of Permanent Magnet Materials

In recent years, tremendous progress has been made in improving both the remanence and coercivity of the NdFeB materials. Table 3 lists the remanences and coercivities of a few commercially available high strength NdFeB materials. As analyzed in Section 3.2, a compromise in choosing a permanent magnet material has to be made between the highest remanence and the coercivity to construct a permanent magnet ECR ion source to be used in the RIB production.

Although the N50 material has the highest energy density and remanence, its coercivity is relatively low compared to other materials. It may be a good candidate for application in non-radiation environments. The N48M is the second but its coercivity is also relatively low. The N45M material has a high remanence of 13.5 kG that is 3.8% higher than the N42H and its coercivity is about 9.7% lower. The lower energy density materials, such as the N42H and

N39SH, all have higher coercivities that are more radiation resistant. However their remanences are somewhat lower and it would require significantly more materials to reach the magnetic field strength compared with the N45H material. Since a compromise has to be made, the N45H material has been chosen for the present development of the high efficiency ECR ion source.

Table 3. Commercially available high strength NdFeB permanent magnet materials

Grade	BH (MGOe)	B_r (kG)	iH_c (kOe)
N39SH	39	12.7	21
N42H	42	13.0	17
N45H	45	13.5	15.5
N48M	48	13.8	12.5
N50	50	14.1	11

4.2 The Magnetic Field Profile

Based on the analysis as discussed in Section 3.2 and 4.1, N45H grade permanent magnet material has been used in the design of the ECR ion source. Using the PANDIRA and PERMAG codes, Dr. Z. Q. Xie has carried out the comprehensive calculations at Berkeley Ion Equipment. At month 2 of the Phase I, a set magnetic field parameters have been determined for a permanent ECR ion source, thereafter named "BIE100".

Shown in Figures 2 and 3 are the BIE100's axial and radial profiles. A compromise was made for the maximum source magnetic field strengths and the cost for practical applications. Microwaves of 14.5 GHz are chosen for the main plasma heating frequency. The designed axial central minimum magnetic field is 4.2 kG that is roughly 80% of the B_{ecr} field for 14.5 GHz microwaves. The maximum fields on axis are 14.3 kG (B_{inj}/B_{ecr} = 2.76) at the injection bias plate and 7.0 kG at the extraction, respectively. This field configuration produces a set of mirrors of ratios: 3.40 with an average gradient of 960 Gauss/cm for the injection side and 1.67 with an average gradient of 400 Gauss/cm for the extraction side, respectively. The peak field at the extraction can be varied from 6.5 to 7.5 kG with different shapes of iron plugs and the optimum will be determined in the source tests. A sextupole magnet provides a radial field with maximum strength of 11 kG (B_{wall}/B_{ecr} = 2.1) at the plasma chamber surface. The sextupole magnet is tapered at both ends to reduce the end-field cancellations of the axial fields. This maintains the

weakest field at the extraction aperture as indicated in Figure 4, which shows a contour topology of the total field strengths for the BIE100 along a pole tip line from the center axis.

Iron plugs are used both at the injection and extraction regions to shape the magnetic field flux in the plasma chamber. Without the iron plugs, the peak fields on axis will be 9.4 kG at the injection and 5.9 kG at the extraction with a minimum center field of 4 kG. As shown in Figure 5, the iron plugs increase the magnetic peak fields on axis up to one third. Though the use of iron plugs adds to the mechanical complexity, it is a well worth effort for the substantially higher peak fields. To reach the same field strengths without the iron plugs but with the same plasma chamber size would require twice the amount of magnet material, which will result in a substantially larger source. Without the iron plugs, the lower magnetic field configuration will still produce good performance and it can be used for the development of a charger breeder for 1+ to N+ ion beams.

Figure 6 shows a magnetic field comparison between the BIE100 and the LBNL AECR-U. The overall magnetic field configuration of the BIE100 is very similar to the LBNL AECR-U's operational field geometry except the field gradients are higher due to the BIE100's shorter plasma chamber length. Though its source magnet assembly is only 1/3 of the size of the AECR-U, the BIE100's plasma chamber volume is more than one half of the AECR-U. The BIE100's magnet volume is smaller than other high field permanent magnet ECR ion sources but the overall field strengths are the highest ever designed for a permanent magnet ECR ion source.
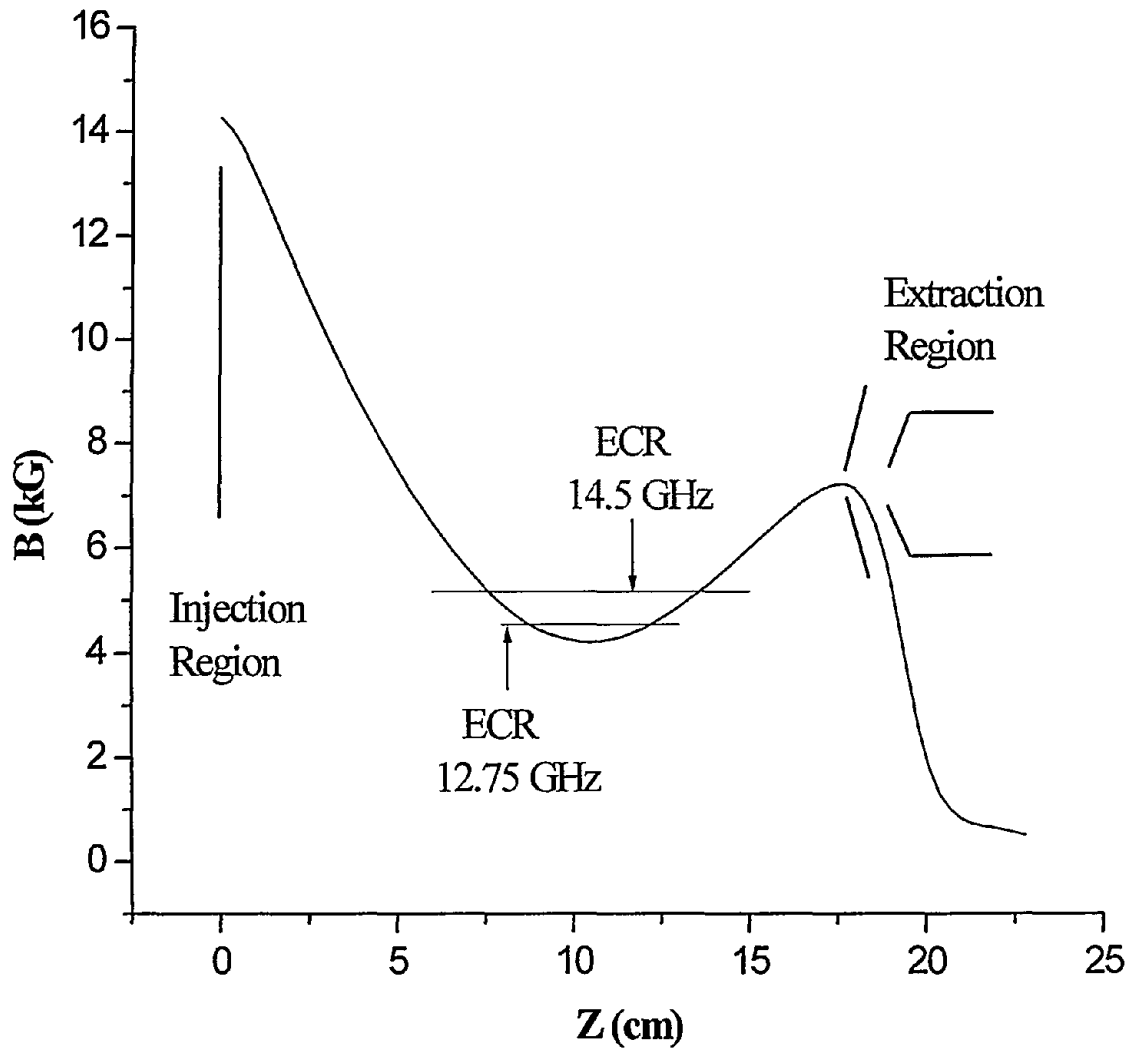
BIE100 Axial Field Profile

Figure 2. This plot shows the axial field profile of the BIE100. The injection peak field at the biasing plate reaches 1.4 Tesla that is about the same as the operational field of the LBNL AECR-U ion source. The two lines in the middle indicate the magnetic field strengths are sufficient for operating with two-frequency plasma heating of 12.75 and 14.5 GHZ.
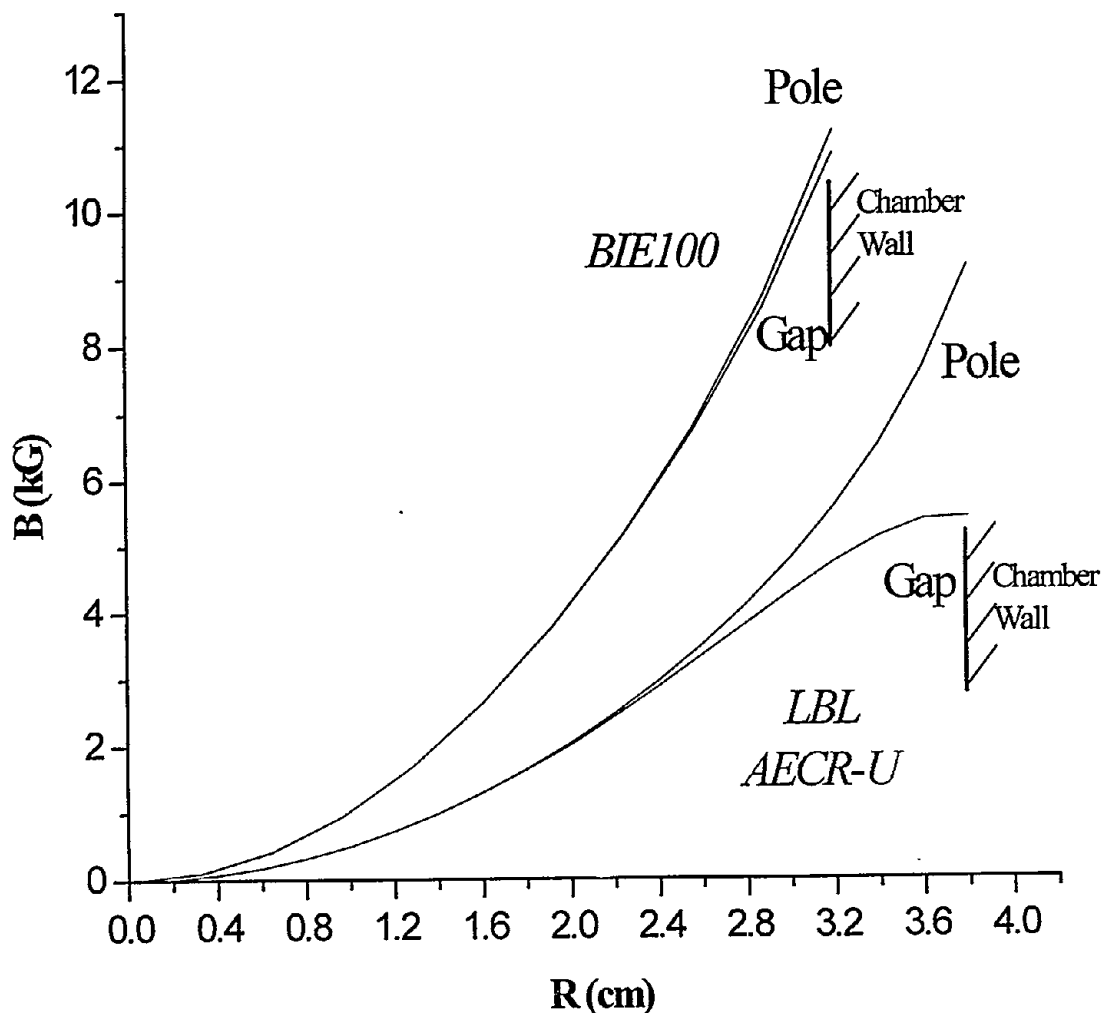
Radial Field Comparison

Figure 3. This figure shows the comparison of the radial field profiles between the BIE100 and the LBNL AECR-U. The maximum field strengths at the plasma chamber surfaces for the BIE100 reach 11 kG, which is about twenty percent higher than the LBNL AECR-U. The gap fields are almost a factor of 2 higher. The BIE100 radial magnetic fields are about a factor of 2 higher than the ECR heating fields. Such a field configuration is expected to provide higher ion extraction efficiencies than the LBNL AECR-U.
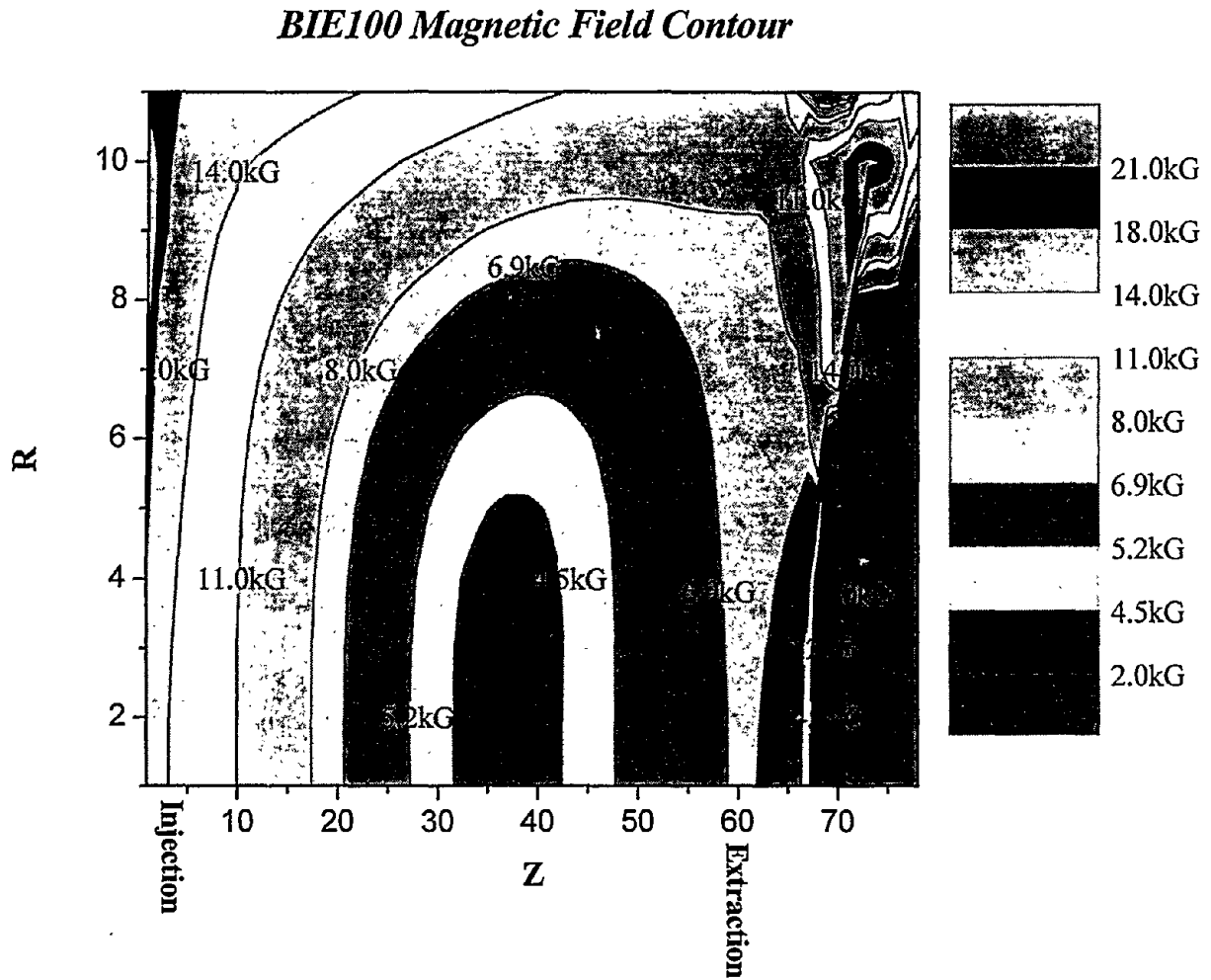
Figure 4. The calculated BIE100 contour plot shows the total magnetic field strengths for a cross-section from the plasma chamber surface along a pole tip line to the central axis. The strong magnetic field strengths are expected to support two-frequency (12.75 and 14.5 GHz at magnetic fields of 4.5 and 5.2 kG) plasma heating for the efficient production of the intermediate and high charge state ion beams.
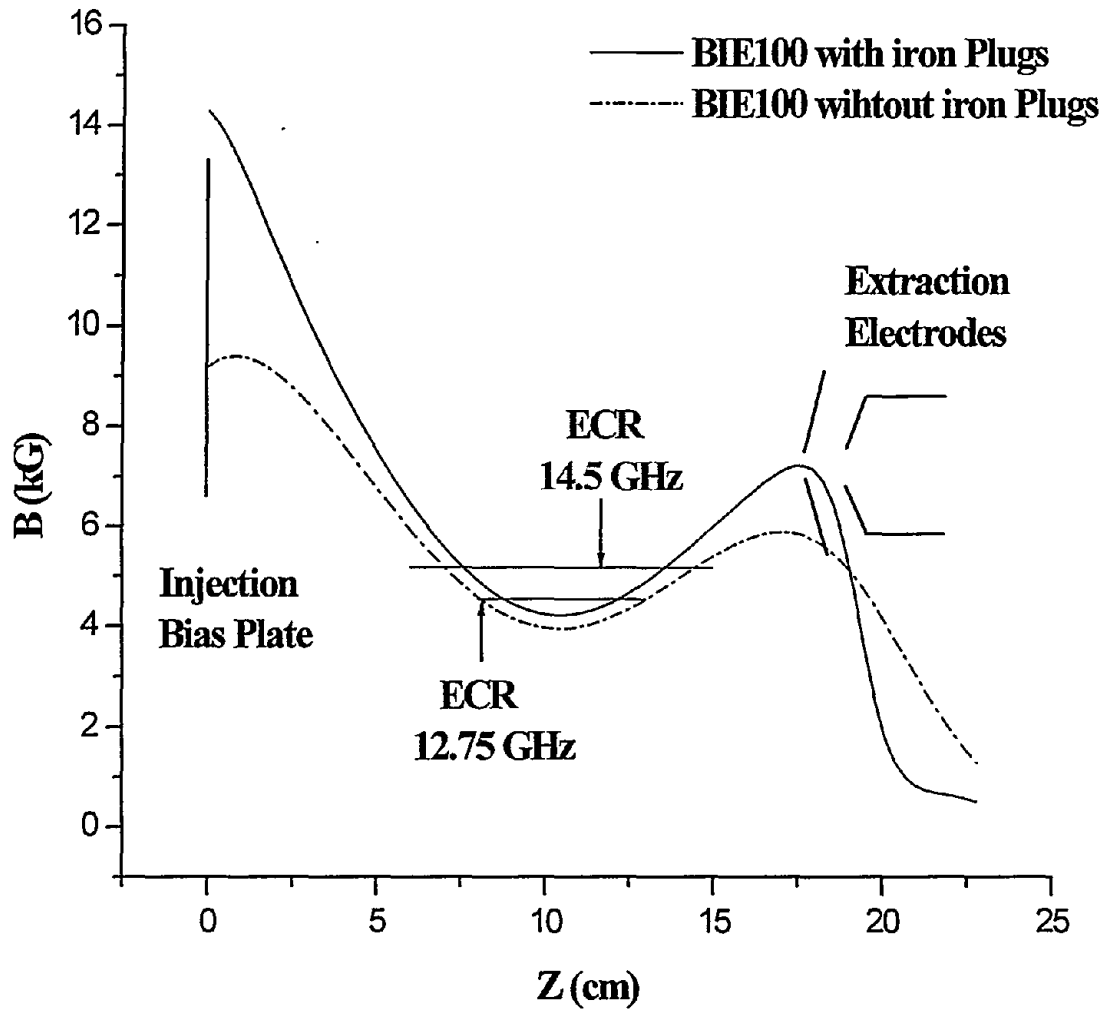
BIE100 Axial Field Profiles

Figure 5. This figure shows the comparison of the radial field profiles between the cases with and without iron plugs to boost the field strengths at both the injection and extraction regions for the BIE100 ion source. With the iron plugs, the injection field strength increases from 0.9 Tesla to 1.4 Tesla and the field strength at the extraction rises from 0.6 Tesla to more than 0.7 Tesla. It would take substantially more permanent magnet material to reach the same field strengths at the two locations if built without the inserted iron plugs. If needed, the BIE100 ion source can operate without the iron plugs but lower field for the test of the 1+ to N+ charge amplifier scheme.
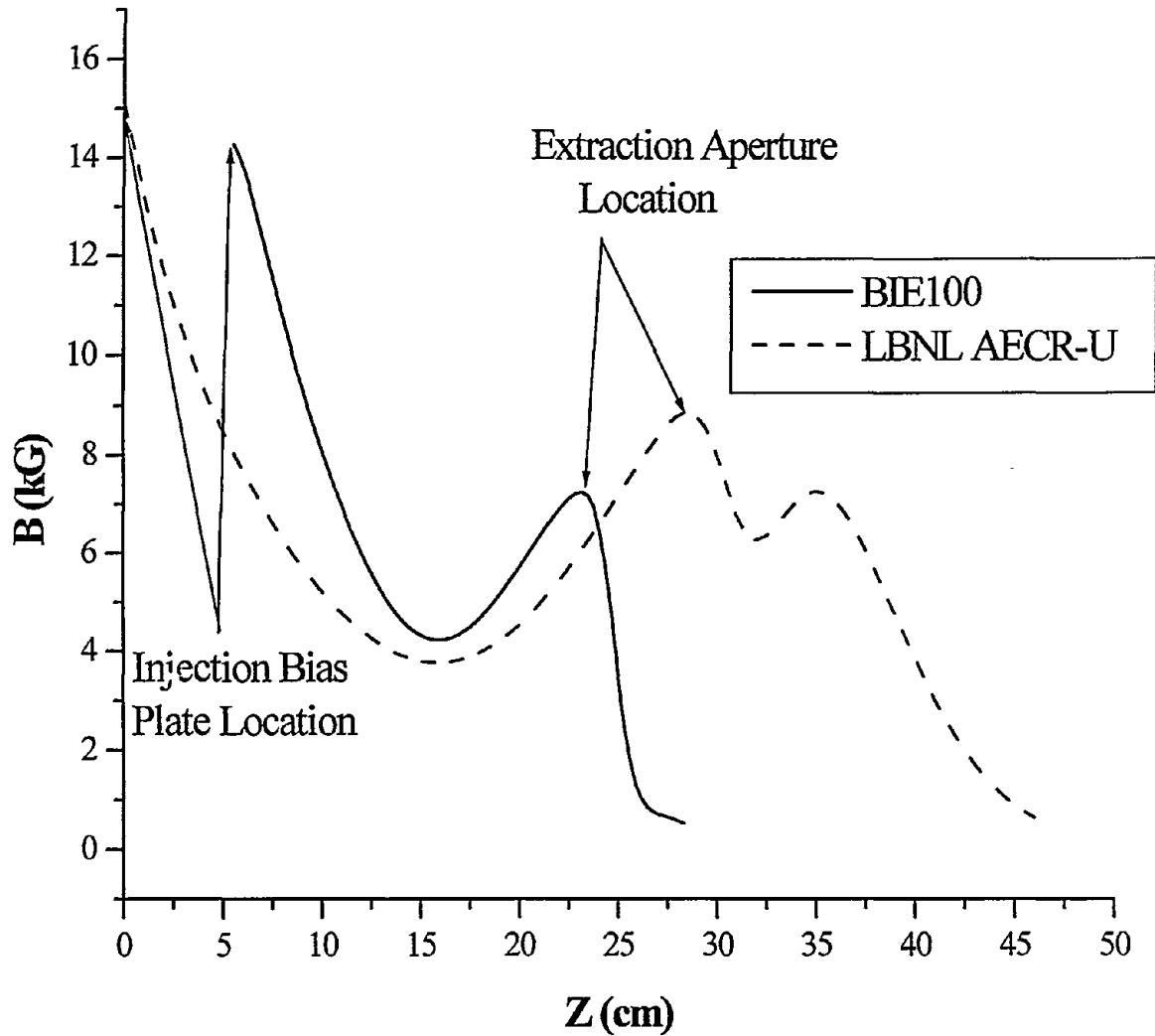
Figure 6. This figure shows the comparison of the axial field profiles between the BIE100 and the LBNL AECR-U. The injection peak fields are about the same for these two ion sources. The designed lower extraction field of the BIE100 is to have better extraction efficiency for the intermediate charge state ion beams.

4.3 Mechanical Engineering Design

Figure 7 shows a mechanical layout of the BIE100 ion source. The magnets, including the aluminum housing, have an outer diameter of 18.5". Four 3" supporting rigid wheels lift the source body 3" above the supporting surface which results in a source height of 21.5". The source magnet assembly is 12.5" long and the total length of the source, including the injection wave guides and extraction mechanism, is 21.75". The plasma chamber is 6.90" (17.5cm) long with an inner diameter of 2.52" (6.4 cm). This plasma chamber will be made from aluminum for its high yield of secondary cold electrons and low sputtering rate. Since this source is not intended for the production of ultra-high charge state ions, there is no radial pumping in the plasma chamber for simplicity. The source pumping relies on the plasma (a good pump) and a 500 l/s Turbo pump located after the extraction electrodes.

Source cooling is provided by a de-ionized water system. There are 6 parallel channels on the aluminum plasma chamber aligned with the six plasma flutes for efficient cooling. A thin aluminum sleeve separates the permanent magnets from the plasma chamber to complete the water path. The cooling channel has an opening of 0.25" width and 0.027" depth that gives a cross-section area of 0.00675 in^2. Eight meters of 5/16" plastic tubing with an inner diameter of about 5/32" will be used in the cooling loop. At a pressure drop of 50 PSI, the flow rate will be about 3 in^3/second (50 cm^3/second). For a 1.5 kW microwave power input, the outlet cooling water will have a temperature rise of less than 8 °C, which is sufficient to protect the source permanent magnets from over heating. For simplicity, a simple accel-deccel extraction mechanism with three fixed electrodes is used to achieve limited capability for optimizing the beam optic matching. The diameter of the extraction aperture is 0.315" (8 mm), the same as the one typically used in ECR ion sources. With adequate insulation in the wave guide high voltage joints, the source will be able to operate with source bias potential up to 40 kV for better beam transport, especially for the intense heavy ion beams.

The source magnet assembly, including the magnet housings of 12.5" long with an outer diameter of 18.5", results in a volume of ~3360 in^3 that is about one third of the LBNL AECR-U built with resistive solenoidal magnets. Without the hot liner, the plasma chamber has an inner diameter of 2.52" with a length of 6.69" resulting in a volume of about 33 in^3 that is about 55%

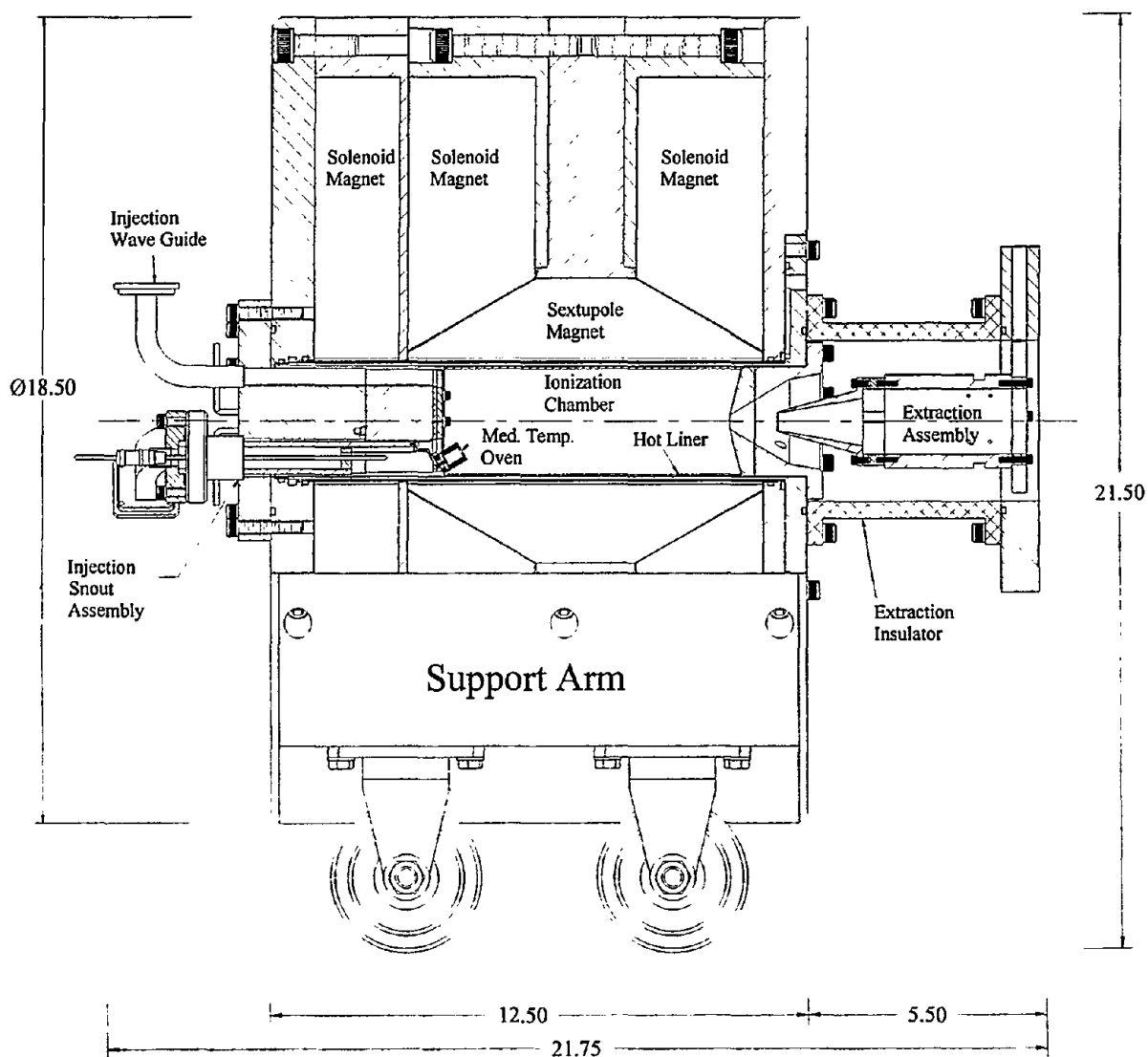of the LBNL AECR-U. The source magnet assembly weighs about 750 lb, about 1/3 of the LBNL AECR-U.

Figure 7. This mechanical layout shows the main components of the designed BIE100 ECR ion source.

4.4 Plasma Heating with Microwaves of Two-frequency

It has been demonstrated that microwaves of various frequencies can be simultaneously launched into and absorbed by a high charge state ECR plasma.[1] The minimum-B magnetic field configuration in an ECR ion source can provide many closed and nested ECR heating surfaces, as graphically shown in Figure 8, if the incoming microwave frequencies match the electron cyclotron frequencies. If two or more significantly different frequencies are used, two or more well separated and nested ECR surfaces will exist in the ECR plasma. With the multiple ECR surfaces, electrons can be heated four times or more for one pass from one mirror end to the other while the electrons are heated only twice in the case of single-frequency heating. Multiple-frequency heating can couple more microwave power with better efficiency into the plasma and it leads to a higher density of the hot electrons, essential to the production of highly charged ions.

Two-frequency plasma heating has been tested with the LBNL AECR and AECR-U.[1] These tests have shown that plasma stability improves and more total microwave power can be launched into the plasma. With the improved plasma stability, the source can operate at lower neutral input, which indicates a lower neutral operating pressure since the mechanical pumping speed is fixed. The lower neutral pressure and higher microwave power lead to a higher "temperature" plasma with increased density of hot electrons.[2] Operation with higher microwave power and lower neutral pressure made possible by the two-frequency plasma heating significantly enhanced the production of highly charged ions.

To efficiently launch more microwave power into the BIE100 plasma, microwaves of 12.75 and 14.5 GHz will be used. The two wave guides are terminated at the injection snout and are separated by 120° to avoid hitting by the plasma. One of the reasons for using these two frequencies is that the ECR field for 12.75 GHz is 4.55 kG that is above the center minimum field. The 12.75 GHz microwave will provide a heating surface of length of 1.2" (3 cm) on axis, nested inside the 2.36" (6 cm) surface for the 14.5 GHz waves. These two heating surfaces together should produce improved performance over either one of them for the production of intermediate and high charge state ion beams. The other reason these two frequencies are chosen is that the system can utilize two identical TWT amplifiers to provide a total microwave power of 1.4 kW (700 W each for frequency from 12.75 to 14.5 GHz) to meet the operation requirement. The portable TWT amplifier weighs 95 lbs and is standard rack mountable with dimensions of 19" x 8.75" x 28" (WxHxL). In addition to the reasons stated above, an
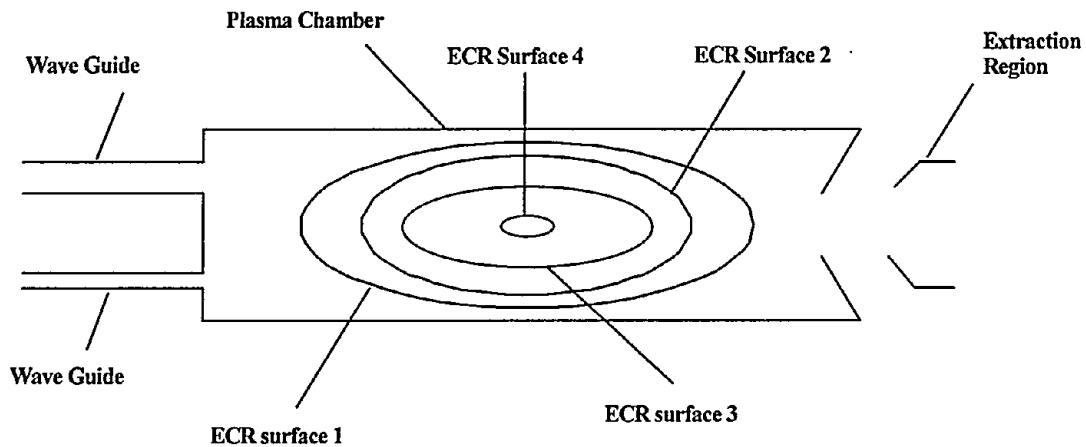
Figure 8. A schematic view of 4 nested ECR surfaces in a high charge state ECR ion source for 4 well-separated frequency waves.

BIE100 Dual Microwave Sources Preliminary Design

A: Frequency counter, optional.
B: Power meter, optional.
C: Sweep frequency source mainframe.
D: 12-14 GHz yig tune oscillator.
E: Sweep frequency source mainframe.
F: 12-14 GHz yig tune oscillator.
G: 700W TWT amplifier.
H: 700W TWT amplifier.

I: Circulator/2KW load.
J: Circulator/2KW load.
K: 40db cross guide coupler, optional.
L: 40db cross guide coupler, optional.
M/N: High voltage isolators.
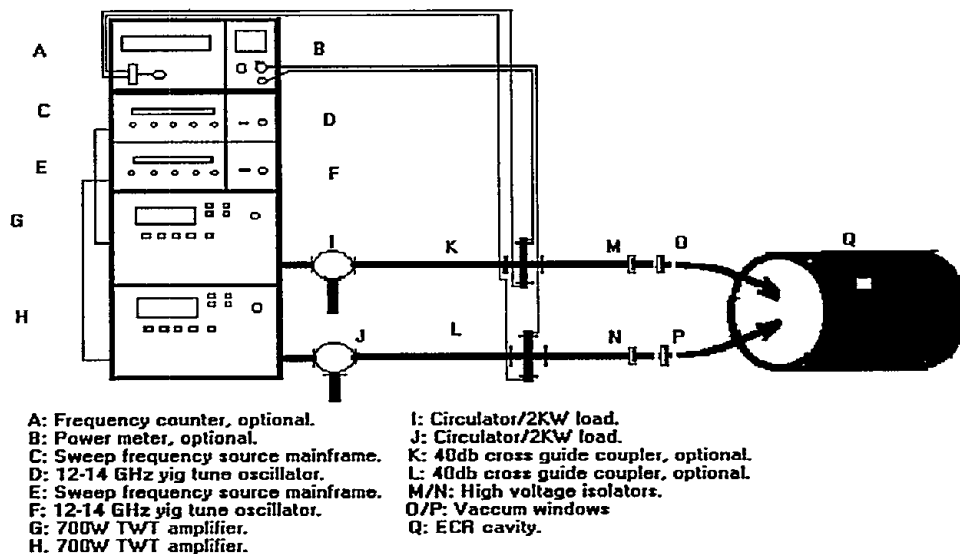O/P: Vaccum windows
Q: ECR cavity.

Figure 9. A schematic view of the two-frequency microwave launching scheme for the BIE100 ECR ion source system.

operational advantage of using the two amplifiers is that one of these amplifiers can be adjusted to an optimum frequency to maintain the operation with somewhat lower performance, in case the other one fails and is being fixed. A schematic view of the two-frequency microwave launch scheme is shown in Figure 9.

References:

[1] Z. Q. Xie and C. M. Lyneis, Rev. Sci. Instrum. 66, (1995) 4218.

[2] Z. Q. Xie, Rev. Sci. Instrum. 69, (1998) 625.

4.5 The RF Heated Hot Liner

Based on the above analysis and for its simplicity, an RF heated hot liner will be tested first to verify its effects on the improvement of ionization efficiencies. The design of this RF heated liner is an annular tube. This tube is 6.89" (17.5 cm) long with an inner diameter of 2.36" (6 cm) and a thickness of 0.04" (1 mm). This tube will be made from alumina. Alumina has low sputtering coefficient and the aluminum is lighter than most of the isotopes to avoid negative mass mixing. In addition, aluminum oxide has been demonstrated to be a good surface coating for an ECR plasma chamber for the production of high charge state ion beams.[1,2] Other materials can be used, such as Ta, W and Ir or other alloys. However these materials can be easily sputtered off by the hot ECR plasma, which will result in a negative mass mixing. A negative mass mixing will lead to lower ionization efficiencies by severely depressing the production of the high charge state rare isotope beams.

The chosen AD-94 grade alumina has good mechanical properties and high dielectric loss at the ECR operating frequencies. The AD-94 has a dielectric loss coefficient of 0.01 (25°C @10 GHz) that is substantially higher than other grades, such as AD-995 (0.001) and AD-998 (0.0004). The surface area of this tube is S = 334 cm^2. Assuming 1 kW microwave power input and the injection and extraction ends covered with the same materials, then the power density per cm^2 will be

$$\mu_s = 2.55 \ W \ cm^{-2}.$$

Based on the thermal radiation in a black box that the radiated energy density μ_s relates to the temperature T as

$$\mu_s = \varepsilon\sigma T^4$$

where σ is the Stefan-Boltzmann constant and ε is the material emissivity. Typically ε is less than 1 and $\varepsilon^{-1/4}$ is slightly greater than 1. For the sake of argument, let ε be 1, then the above equation leads to

$$T = (\mu_s/\sigma)^{1/4} = 819 \,°K = 546 \,°C.$$

When the input microwave power rises to 1.4 kW, the liner could be heated to about 618 °C. Such a temperature can be sufficient for an ECR operating with may low temperature solid isotopes.

The thickness of the alumina tube and the thermal insulation reduce the effective plasma chamber bore of the BIE100 from 6.4 to 6.0 cm while the maximum radial field strength at the chamber surface decreases from 1.1 to 0.97 Tesla. A 12% lower radial field of the BIE100 is acceptable in most cases for the production of the intermediate and some high charge state ion beams.

References:

[1] T. Nakagawa, Jpn. J. Appl. Phys. **30**, 930 (1991).

[2] Z.Q. Xie and C.M. Lyneis, Rev. Sci. Instrum. **65**, 2947 (1994).

4.6 Resistively Heated Oven for Solid Materials

A resistively heated miniature oven has been designed, as shown in Figure 10, for operation with solid materials. This miniature oven design is similar to but smaller than the one used at National Superconducting Cyclotron Laboratory, Michigan State University.[1] The overall size of this oven is 0.5" in diameter and 0.7" in length. The material loading volume is ~0.015 in^3 (0.25 cm^3) that is sufficient to load solid materials up to hundreds of milligrams, depending upon the elements or compounds. This oven will be introduced off-axially, as indicated in Figure 10, into the plasma chamber for good vapor acceptance. At about 50 W of power (~10V/5A), a double wound W-Re wire will heat the oven up to about 1400 °C. This temperature covers a great variety of solid materials to produce adequate vapor pressures for operations with an ECR plasma. In the Phase II R&D, this miniature oven will be used to investigate the ionization efficiency for the rare solid isotopes, for instance ^{48}Ca, and the production of intense heavy ion

beams, such as Bi and Au. The production of intense Bi or Au ion beams will indicate the source capability of producing uranium ion beams for about the same charge states. A higher temperature oven will be designed and fabricated later in Phase II or post Phase II development for the production of intense uranium ion beams.
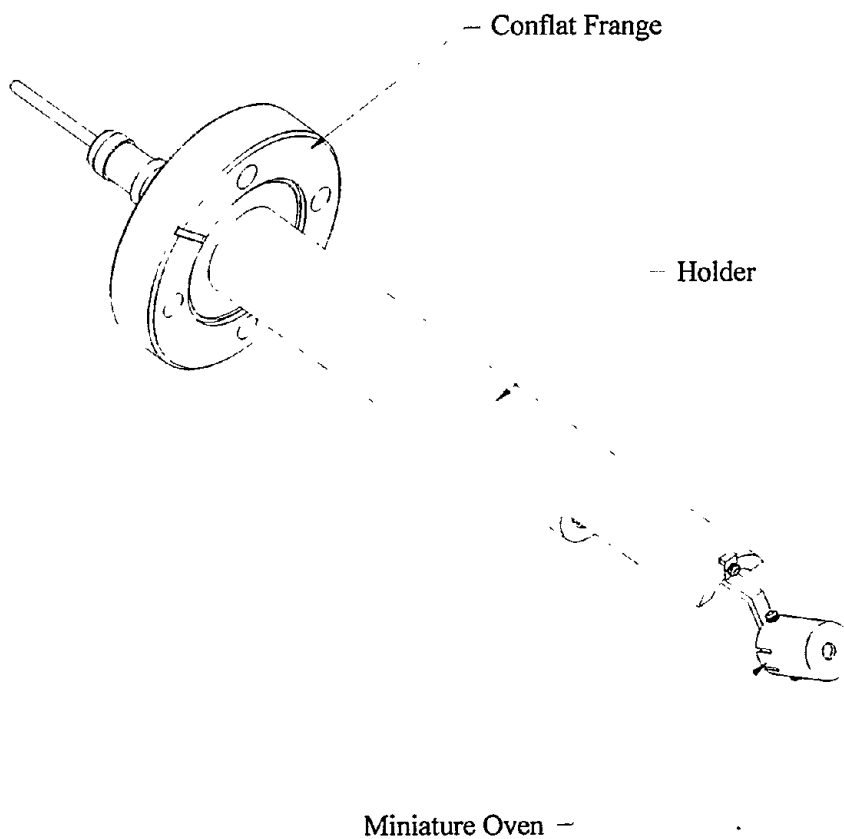
— Conflat Frange

— Holder

Miniature Oven —

Figure 10. An assembly view of the miniature oven that is to be used for the production of solid ion beams.

References:

[1] R. Harkewicz and D. Cole, proceedings of the 13th International Workshop on ECR Ion Sources, College Station, Texas, Edited by D. May, Feb 1997.

4.7 System Test Bench

To fully evaluate the efficiency of the BIE100 ion source system, a tech bench is needed. This test bench should be equipped with an analysis magnet. This analysis magnet should have an un-normalized acceptance at least of 150 π mm mr for both horizontal and vertical planes. Figure 11 illustrates a layout of the test bench for the BIE100 ion source. A metal frame will hold all the components. In addition to the ion source system and the beam analysis magnet, the test bench will consist of a beam transport line, a vacuum pumping system, a de-ionized cooling water system, two vacuum gauges, floating gases bottles and control valves, and a Faraday Cup assembly for measuring the ion beam currents. The analysis magnet is a water-cooled 90° double focusing magnet with an aperture of 4" (horizontal) and 3.0" (vertical). The maximum field strength of the analysis magnet will reach 7 kG, strong enough to bend Ar^{1+} ion beam at energy of 40 keV. The magnet's bending radius of 11.8" (30 cm) will provide a resolution power of ~60 that is sufficient to resolve most of the high and intermediate charge state ions. Two 500 l/s turbo pumps are used to evacuate the beam line with base pressure to a few x 10^{-8} Torr. The two 12.75 to 14.5 GHz microwave amplifiers with RF drivers will be located in the left side of the bench for easy operation. This compact test bench can be easily moved to a DOE's national facility to carry out the actual testing and evaluation with radioactive isotopes.

The electrical and some mechanical details of the test bench will be finalized in Phase II so the space available and the infrastructures at the actual testing site can be taken into account.
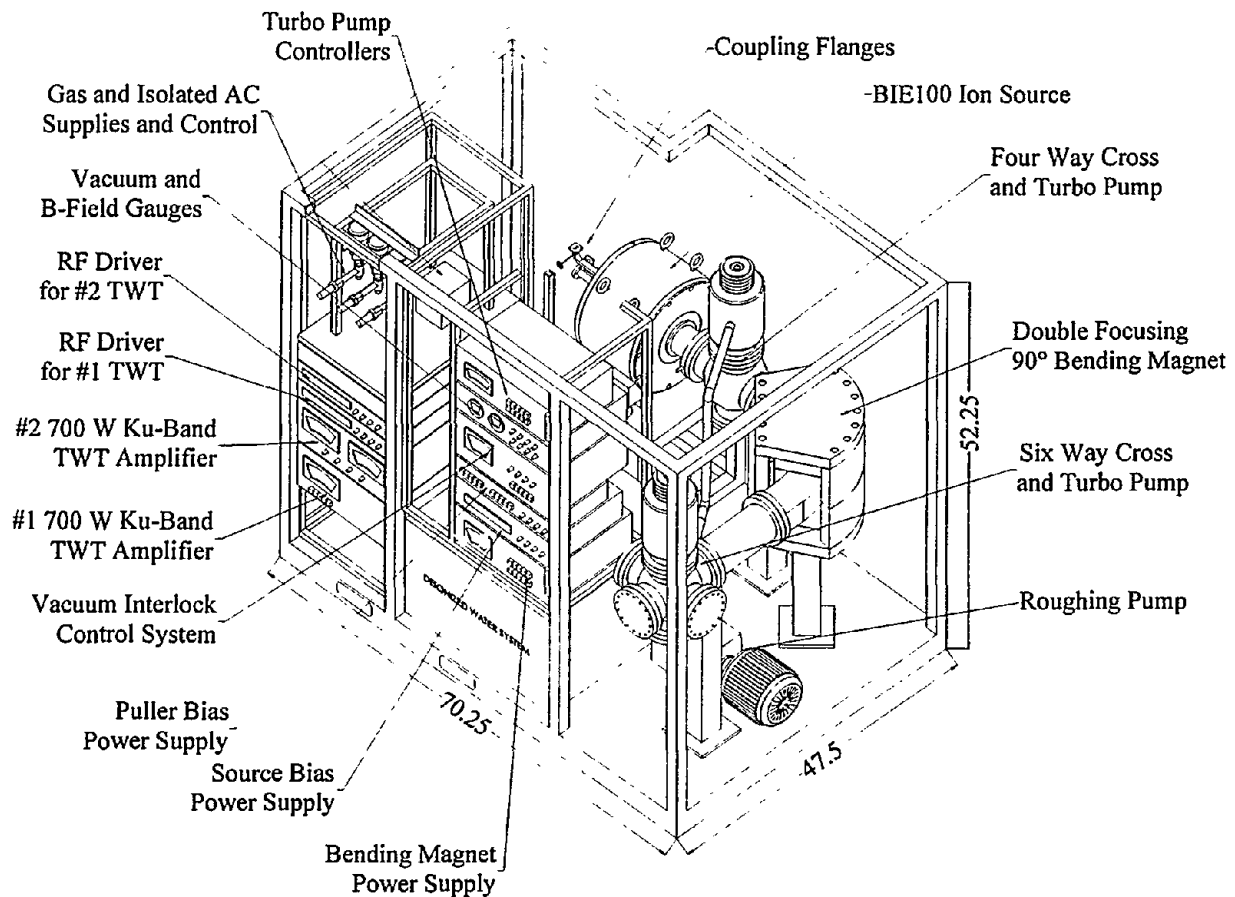
Figure 11. An illustrative view of the test bench shows all the main components needed for characterizing the designed BIE100 ECR ion source system.

5.   SYSTEM COST ESTIMATES

Construction of a high performance ECR ion source is relatively expensive, especially when the source is built with either resistive or superconducting magnets. Listed in Table 4 are the itemized cost estimates for the designed BIE100 ion source system, including the test bench components. With the elimination of more than one hundred kW of DC power supplies, the total estimated component cost for the designed BIE100 and the test bench is ~ $500k. Compared on the same bases, the component cost for a high performance ECR ion source system built with resistive magnets will be about $650 k while a high field superconducting ECR ion source system could easily cost more than $1.5 M. Therefore the cost for the BIE100 ion source system

is considerably lower than the other two types of ECR ion sources, not to mention its substantially lower engineering and installation costs. Another advantage of the BIE100 ECR ion source system is that the total operation power is less than 10 kW that is substantially lower than the power required for an ECR ion source built with resistive magnets.

Table 4.   *Cost Breakdown for the BIE100 System*

Item	Description	QTY	Est'd $(k)
1	Source Magnet Assembly (BIE100-01-14)	1 set	150
2	Plasma Chamber. & Related Parts (BIE100-15 - 32)	1 each	12
3	RF Heated Chamber Hot Liner (BIE100-17)	2	2
4	Alumina Insulator and spacer (BIE100-20,-28)	2-10	3
5	Medium Temp. Oven Assembly (BIE100-40)	1 set	5
6	Source Magnet Assembly Fixture	1 set	3
7	Source Assembly Bolts and Screws	1 set	1
8	500 l/s Turbo Pump & Controller (second hand)	2 sets	30
9	Beam Analysis Magnet & Power Supply	1 set	50
10	Beam Analysis Magnet Hall Probe	1 set	3.5
11	Beam Line Pipes & Crosses (6" dia. for ~ 2 m)	1 set	4
12	Roughing Lines, Valves and Mech. Pump	1 set	5
13	Faraday Cup Assembly	1 set	3
14	HV Supply (40 kV/30 mA)	1	4.5
15	Puller HV Supply (-10 kV/5 mA)	1	2
16	Vacuum Gauge and Controls (second hand)	2 sets	3.5
17	700 W 12.75-14.5 GHz TWT Amplifier (ETM)	2	110
18	1 kW External 4-Port Circulator Set	2 sets	6
19	RF Drive Generator (12 to 15 GHz)	2	5
20	Microwave Guides and Bends	1 set	1.5
21	Microwave vacuum window (WR75)	3	1.5
21	Microwave Guides HV 40 kV Stand-Off	2	2
22	Test Bench Frame	1	5
23	De-ionized Water Cooling System	1	5
24	Gas Flow Control Valves	3	3.5
25	Gas Pressure Regulator	3	2
26	Calibrated Leak gases (O_2, Ar, Ne, Kr & Xe)	1 each	8
27	System Vacuum Safety Control Relay Circuit	1	3
28	Source Lead Shielding	1 set	1
29	40 kV Isolated Transformer for the Med. T. Oven	1	2
30	X-Y Chat Recorder	1	3

Total: **$440 k**

6. ANTICIPATED BENEFITS

6.1 Applications to DOE's RIB Production

If funded for Phase II and possibly III, Berkeley Ion Equipment, Inc. will fabricate the ECR ion source system and the test bench to evaluate the ionization efficiencies of the ion source system. BIE will also closely collaborate with ATLAS at Argonne National Laboratory to carry out actual efficiency evaluation using the a few rare isotopes produced with the Dynamitron at ATLAS, ANL. It will eventually provide alternative injector techniques for the post-acceleration at the DOE's RIB and ISOL facilities. In addition, the fabricated ion source and the hot liner in Phase II can be used for the R&D of other injector schemes, for example, the 1+ to N+ scheme.

6.2 Other Applications

Besides the RIB and ISOL applications in the production of high and intermediate charge state rare ion beams, the design features of the system, such as the combination of ECR/hot-liner, can be used for more efficient production of stable solid ion beams for nuclear science research. The hot plasma chamber liner inserted in an ECR ion source can cycle many absorbed solid materials from the plasma chamber surfaces back into the plasma to achieve higher ionization efficiencies. This will greatly benefit the production of the stable solid ions, especially the rare isotopes, such as ^{48}Ca and ^{36}S, for nuclear science research. If the BIE100 ion source is capable of producing intense high charge state heavy ion beams, for example, bismuth and uranium, it will provide alternative injector for the heavy ion drivers in the ISOL and RIB facilities. By operating in the after-glow mode (such as used in the CERN lead injector), it could provide injector technique for the synchrotrons, such as the RHIC heavy ion collider at Brookhaven National Laboratory.

6.3 Commercial Potential

Berkeley Ion Equipment, Inc. (BIE) is a small company founded in 1997 to design, fabricate and market high performance ion sources, MeV machines and related equipment for ion implantation, ion milling and material surface modification in both academic research and industry. BIE is currently the only company in the US specializes in custom design and fabrication of high performance, high charge state ECR ion sources. The developed all permanent magnet ECR ion source is capable of producing high charge state ions for elements

from hydrogen to uranium and is high voltage platform compatible. It will be one of the standard BIE products that can be integrated into the industry existing ion implanters or academic researches for high energy ion implantation, ion milling, etc. It also will be a crucial component of the new MeV machines built with high charge state ECR ion source, designed and fabricated by BIE, for applications mentioned above.

ACKNOWLEDGMENTS